The Prediction of Wind-Driven Coastal Circulation

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LONG-TERM GOALS

To develop forecast systems for wind-driven coastal ocean flow fields.

OBJECTIVES

To understand the dynamics of, and to build a predictive capability for, wind-driven mesoscale oceanographic processes (2-50 km horizontal space scales, 2-10 day time scales) over the continental shelf as influenced by temporal and spatial variability of the atmospheric forcing, by spatial variability of the continental margin, and by internal mixing related to small-scale turbulence. The ocean variability of interest includes the physical processes associated with energetic alongshore coastal jets, upwelling and downwelling fronts, and eddies. To develop a practical method for the assimilation of HF-radar derived surface currents and other measurements into a primitive equation coastal ocean model.

APPROACH

This National Oceanographic Partnership Program project combines modeling, data assimilation and an observational program off Oregon. High-resolution, three-dimensional coastal ocean circulation models utilizing the Princeton Ocean Model (POM) are being applied to an Oregon coastal region for direct simulations, data assimilation and process studies. Two model configurations are used. Both have limited-area, high-resolution grids with realistic Oregon coastal topography. The first configuration extends 600 km alongshore, from 41.7°N to 47°N, and 250 km offshore and contains three open boundaries. The second configuration is of similar size, but involves idealized periodic

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boundary conditions at the northern and southern boundaries. A regional atmospheric model is used to estimate surface forcing fields and to study the dynamics of the coastal lower atmosphere using triply nested 36 km/12 km/4 km grids. The ocean models are being forced by observed winds and heat flux and the results compared with observations. The limited-area, open-boundary circulation ocean model is also being driven by fluxes from the regional atmospheric model. The sensitivity of model-produced upwelling circulation to turbulent closure schemes is being investigated. The Mellor-Yamada level 2.5 scheme, the k-epsilon closure, and the K-Profile Paramaterization (KPP) are being utilized. The structure and strength of the resulting vertical mixing is studied and compared. In addition, the effects of the different schemes on the mesoscale circulation are assessed. A practical, sub-optimal, sequential data assimilation system has been developed for implementation with POM (Oke et al., 2000). Inhomogeneous and anisotropic estimates of forecast error covariances, used to project information from the surface current measurements onto the full three-dimensional model grid, are obtained by assuming that the forecast error covariances are stationary and are proportional to the "typical" cross-correlations between modeled variables.

The observational program includes long-term measurements from the OSU Coastal Radar System presently deployed near Newport. During summer 1999, NOAA ETL partners expanded the land-based radar coverage (J. Harlan) and obtained vertical wind profiles using an upward-looking RASS profiler on the coast (J. Wilczak). Satellite-sensed sea surface temperature and roughness are being made available by Ocean Imaging (J. Svejkovsky). Bi-weekly hydrographic and zooplankton sampling was conducted off Newport by NOAA NMFS (W. Peterson). CODAR Ocean Sensors (D. Barrick, B. Lipa) worked on testing the feasibility of improving the direction-finding capabilities of their standard SeaSonde antenna by including up to four additional whip antennae.

Additional measurements by OSU PIs included bi-weekly hydrographic sampling off Newport obtained using a small towed, undulating vehicle (MiniBAT) (Austin et al., 2000). During May to August 1999, three moorings equipped with current, temperature and conductivity sensors throughout the water column were deployed off Newport (Boyd et al., 2000). One of the moorings measured surface winds, pressure, air temperature and solar insolation, and telemetered those data to shore. During July and August, atmospheric soundings were made at Newport on selected days. A three-week cruise aboard the R/V Wecoma was made during July 1999. High-resolution hydrographic, bio-optical, velocity and microstructure data throughout the water column were collected in a region near Newport encompassing the coverage of the land-based radar. The hydrographic and velocity fields are being used to initialize and provide ongoing data for assimilation into the coastal model. The microstructure data are being used with the model to assess the role of small scale turbulence in determining the mesoscale structure of the flow and hydrographic fields.

WORK COMPLETED

The wind stress field in the Oregon coastal zone during June through August 1999 was estimated from a regional mesoscale atmospheric model, supplemented by moored and coastal surface observations and a land-based 915 MHz RASS wind profiler.

The limited-area, periodic POM was configured for the sub-inertial continental shelf circulation for summer 1999 off Oregon. A series of numerical experiments were performed investigating the models sensitivity to wind forcing, surface heating, Columbia River forcing, model domain size and initial conditions. The model results were compared with in situ velocity, temperature and salinity measurements obtained during the 1999 intensive OSU NOPP field season. Comparisons were made

with measurements from moored instruments, MiniBAT surveys, SeaSoar surveys and shipboard ADCP transects. The limited-area, open boundary POM was forced both by buoy measured winds assumed spatially uniform and by spatially variable wind stress fields from the mesoscale atmospheric model. The model results were compared with the moored current measurements. The effects of different turbulent parameterization schemes were examined in both two-dimensional (alongshore uniform) and three-dimensional numerical experiments.

The forecast error covariance fields for the data assimilation system were calculated from an ensemble of 17 model runs where the model was forced with observed winds from 17 different "typical" summers (July and August) between 1969 and 1998. In order to overcome difficulties with primitive equation initialization and assimilation of low-pass filtered data into a model admitting fluctuations at all frequencies, a time-distributed averaging procedure was developed. The effectiveness of the data assimilation system was assessed by performing a series of assimilation experiments for summer 1998. An assessment of the sub-surface analyzed velocity fields was made through comparisons with independent velocity measurements from a moored ADP located over the mid-shelf. Statistical consistency checks were performed in order to test further the validity of the estimated forecast error covariances. Additionally, insight into the sources of model error were gained by analyzing the modeled dynamical balances and assessing the role of the correction that was derived from the assimilation.

Observations of temperature, salinity, chlorophyll fluorescence and light transmission from over 20 cross-shelf sections obtained using the MiniBAT vehicle have been processed and are being analyzed (Austin et al., 2000). Over 1300 profiles of turbulence parameters and light backscatter have been processed and are being used to estimate bottom stress and to investigate details of the bottom boundary layer over the shelf. Over 12,000 CTD profiles obtained using the towed vehicle SeaSoar have been processed and used to form vertical sections and horizontal maps which, when combined with shipboard ADCP velocity measurements, are being used to investigate mesoscale dynamics. Measurements of the Inherent Optical Properties (IOP) using a nine-wavelength absorption and attenuation meter deployed in the flow-through system of the ship are used to develop high-spatial resolution 2-D maps at 5 m depth (~20 m between samples). The 2-D maps are extended to 3-D with data collected on the SeaSoar (vertical resolution ~1m, horizontal resolution < 1 km). The optical measurements are used to estimate chlorophyll, sediment, and colored dissolved organic concentrations and to relate their distributions to physical features (upwelling front, submarine banks, Columbia River plume, etc.) and to SeaWiFS imagery. Moored observations from spring through summer 1999 have been processed (Boyd et al., 2000) and are being used to study the response of the coastal ocean to wind forcing and to verify the numerical ocean models.

RESULTS

Comparison of atmospheric model results with observations (Figure 1b) suggests that the model performed sufficiently well to provide useful estimates of wind stress in regions where wind measurements were not available (Samelson et al., 2000). Both the mean (Figure 1a) and variable components of model alongshore wind stress increase by factors of 3-4 from north to south along the Oregon coast. There is evidence of orographic intensification near Cape Blanco, which is supported by previous aircraft and ship observations during August 1995. Differences between model and buoy surface air temperatures (Figure 1c) are highly correlated at 16-18 hour lag with southward stress, and evidently arise because the atmospheric model sea surface temperature analysis does not resolve the cold upwelled water near the coast. This suggests that ocean upwelling modifies coastal surface air

temperatures by 1-5° C over time scales of 12-24 hours. The low-level atmospheric jet undergoes diurnal horizontal and vertical displacements that are in some ways similar to what has been observed and modeled along the California coast (Bielli et al., 2000). There is also a minimum in northerly wind between 1500 and 1800 UTC (0700 and 1000 local time) and a double maximum of offshore flow above the marine boundary layer. The advection of alongshore wind is an important term in the alongshore force balance. Thus, in contrast to the previous results for the California coast, the diurnal circulation is fundamentally three-dimensional in the coastal zone and as far as 100 km offshore.

The 1999 continental shelf circulation modeled by the limited-area, periodic POM is in good agreement with observations on the shelf (Figure 2). The magnitude of the complex cross-correlation between observed and modeled currents are approximately 0.8 over the inner shelf and 0.5 over the mid-shelf. The correlation between observed and modeled temperature are up to 0.93 over the inner shelf and 0.76 over the mid-shelf. The sensitivity experiments indicated that surface heating and Columbia River forcing are important. The average correlation coefficient between observed and modeled temperature over the mid- and inner shelf is approximately 0.4 without surface heating and greater than 0.7 with surface heating. The comparison between modeled and observed mean and standard deviations of potential density from the MiniBAT surveys is significantly improved when idealized Columbia River forcing is included in the model configuration. The modeled dynamical balances are currently under investigation. Results from the limited-area, open boundary POM show improved agreement of modeled and observed velocities with forcing by the spatially variable winds from the mesoscale atmospheric model compared with forcing by spatially uniform buoy winds. Results from the numerical experiments comparing effects of turbulence schemes show that substantial differences in model-predicted vertical mixing may exist and that they occur primarily in the upwelling frontal region and in the bottom boundary layer. The reasons for these differences and their implications for the mesoscale flow are being investigated.

The effectiveness of the assimilation system (Figure 3) has been demonstrated by assimilating HF-radar derived surface currents into POM and comparing the analyzed sub-surface velocities over the mid-shelf to independent observations during summer 1998 (Oke et al., 2000). The correlation coefficient of the modeled depth-averaged velocities without assimilation is 0.42 and with assimilation is 0.76. This significant improvement demonstrates the potential of the assimilation system. The analysis of the modeled dynamical balances indicates that the primary source of model error is uncertainties in the spatial details of the applied wind stress. Applications of the data assimilation system for summer 1999 are in progress.

The 3D SeaSoar hydrographic surveys show that the midshelf, southward coastal upwelling jet follows the Heceta Bank topography as it widens offshore (Figure 4). The jet reaches the southern end of the Bank, where the shelfbreak turns almost 90 degrees back toward the coast. The ensuing adjustment involves the offshelf transport of coastal water and the material it contains. By creating an E-W perturbation in the coastal upwelling front, an alongshore pressure gradient is introduced. Together with changes in the wind forcing which occur with a 2-5 day period (Figure 2), an alongshore pressure gradient can drive flow back to the north. This leads to northward flow on the inshore side of the Bank and even recirculation around the entire Bank system. Detailed sections across the shelf upstream and downstream of a midshelf submarine bank demonstrate the role of bottom topography in directing the alongshelf upwelling jet offshore and mixing the overlying water column (Figure 4).

Measurements from the turbulence profiling were used to estimate the mean bottom stress at 0.015 N m^{-2} with a standard deviation of 0.012 N m^{-2}, consistent with similar measurements made over the shelf. Stresses in excess of 0.02 n m^{-2} occurred near topographic rises, approximately 10 m in vertical extent, at the 90 and 150 m isobaths. The turbulence profiles are also being used to investigate the vertical stucture of dimensionless turbulent intensity in the bottom boundary layer.

IMPACT/APPLICATIONS

A verified predictive capability for wind-driven coastal circulation based on remotely sensed data and a minimum of in situ data would be of great use for navigation, search and rescue, pollutant transport and ecosystem studies since much of the world's coastal oceans are wind driven.

TRANSITIONS

The optical data from the July 1999 cruise are being used by S. Pegau under ONR HyCODE. The biweekly data on sea surface nitrate and chlorophyll and water-column-integrated zooplankton biomass for 1997-1999 are being used by Y. Spitz, J. Allen and P. Newberger to validate their ecosystem model of this region funded under the NSF Coastal Ocean Processes (CoOP) program.

RELATED PROJECTS

Some aspects of the ocean modeling and data assimilation studies are jointly funded by NSF Grant OCE-9711481 (CoOP) and by ONR Grants N00014-98-1-0043 and N00014-94-1-0926. The OSU NOPP atmospheric PIs collaborated with and supported the remote sensing, aircraft and modeling efforts of M. Wetzel (DRI, Reno), G. Vali (U. Wyoming) and W. Thompson (NRL Monterey) associated with the COSAT experiment off the Oregon coast during August 1999.

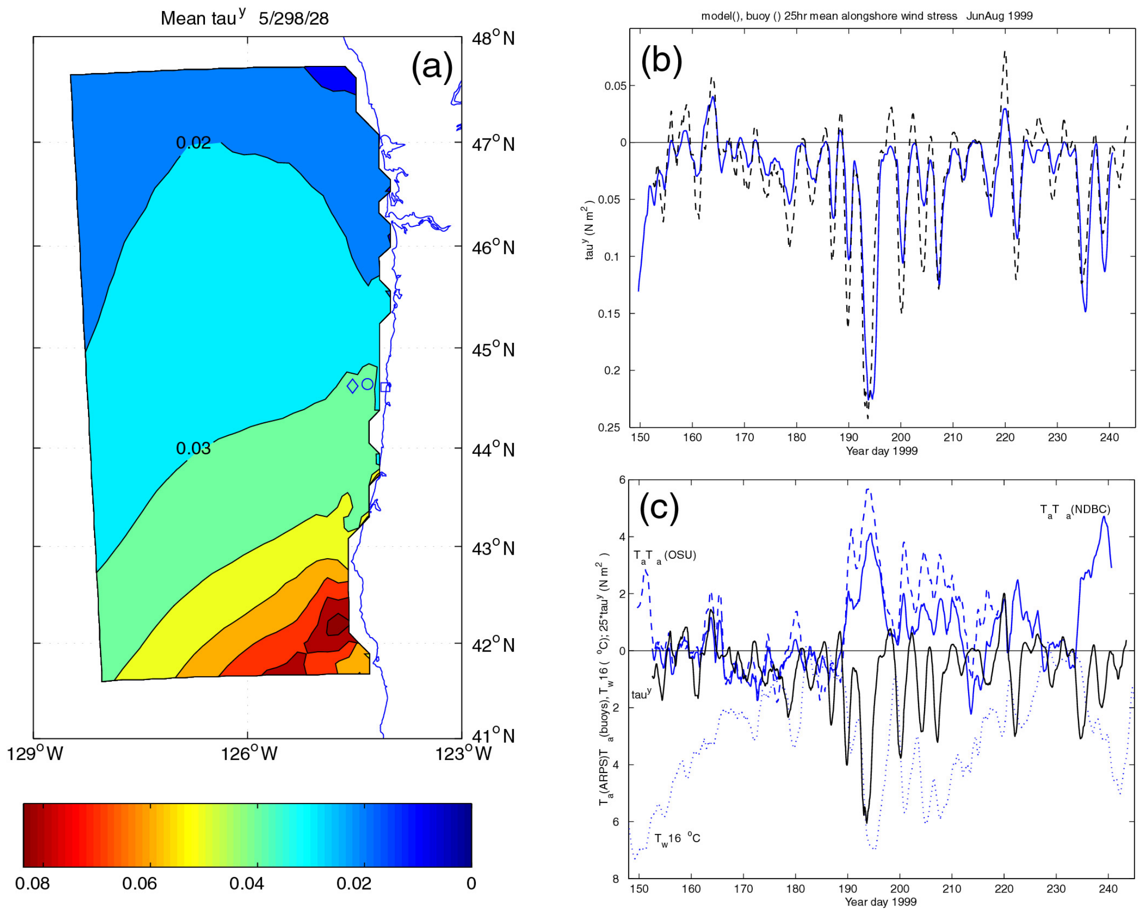

Figure 1: (a) Mean north-south wind stress for June through August 1999 (contour interval 0.01 N m^{-2}. The locations of the NDBC 46050 (diamond) and OSU (circle) buoys and the Newport CMAN/RASS (square) sites are indicated. (b) Model (solid line) and NDBC 46050 buoy (dashed) 25-hr mean north-south wind stress vs. year-day 1999. (c) Alongshore wind stress at NDBC 46050 (thick solid line) and differences of model and NDBC 46050 (thin solid) and model and OSU buoy (dashed) surface air temperatures (deg-C) vs. year-day 1999. The wind stress time series has been multiplied by 25, so the effective units of stress are 0.04 N m^{-2}. The 2-m ocean temperature (deg-C, with a constant offset of -16C) at the OSU buoy is also shown for comparison (dotted). All time series have been smoothed with a 25-hr running mean.

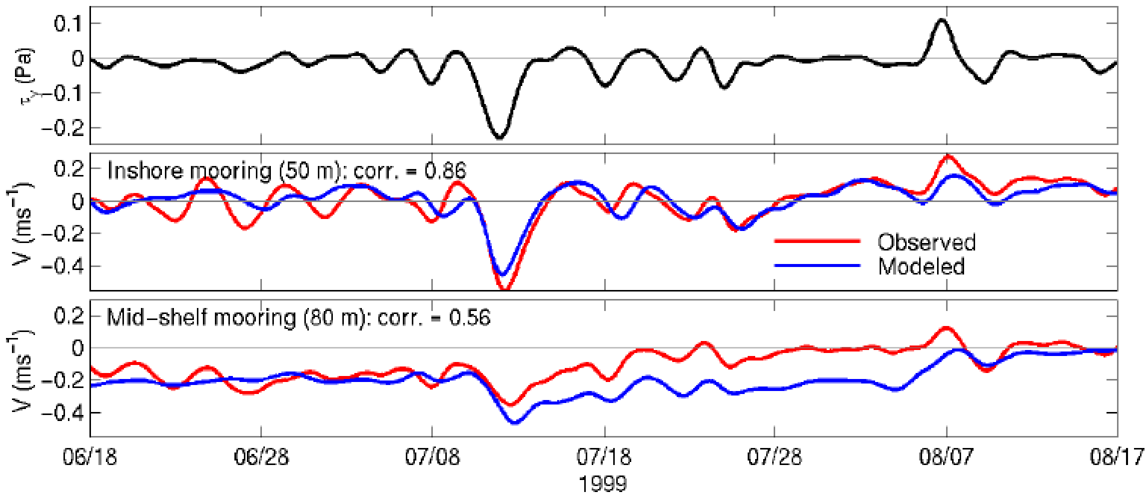

Figure 2: Comparison of model-only (blue) and observed (red) depth-averaged alongshore currents for summer 1999 showing the applied wind stress from winds at Newport, OR (top); observed and modeled currents from the inshore mooring in 50 m water depth (middle) and from the mid-shelf mooring in 80 m water depth.

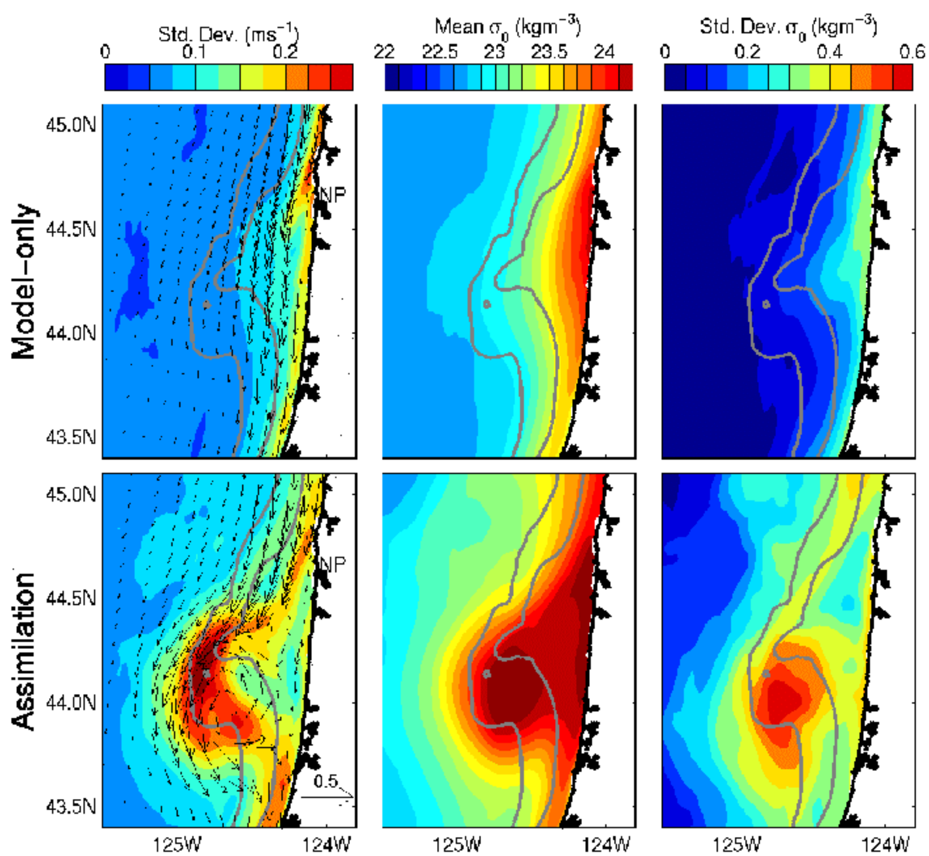

Figure 3: Comparison of surface fields from model-only (top) and assimilation (bottom) experiments for summer 1998. Mean surface velocity vectors overlaying the standard deviation of velocity magnitudes (left); Mean (middle) and standard deviation (right) of surface density. The 100 m and 200 m isobaths are contoured in gray (adapted from Oke et al., 2000).

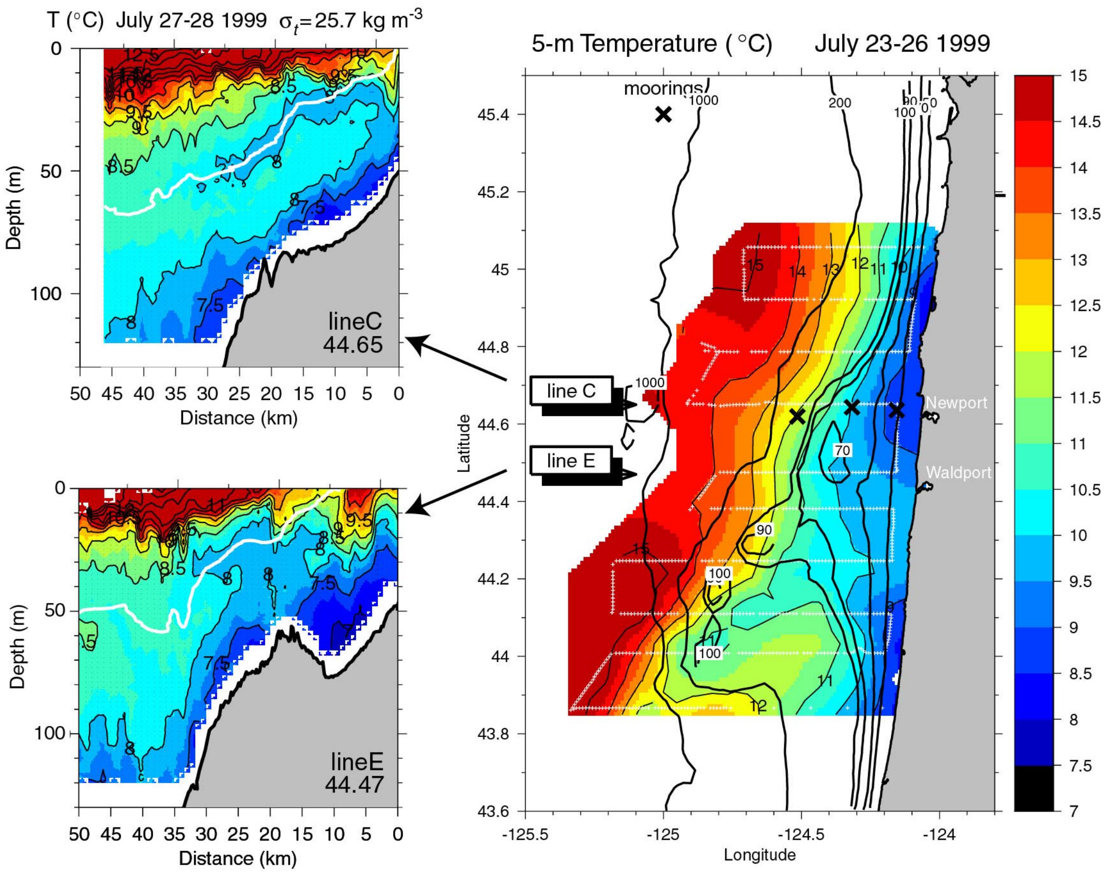

Figure 4. Temperature at 5 m from a SeaSoar survey during 23-26 July 1999. Bottom topography in meters. Vertical sections of temperature along lines C and E just upstream and downstream of Stonewall Bank. White curve is the 25.7 kg m^{-3} density anomaly contour.

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